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Self-Optimization Simulation Model of Short-Term Cascaded Hydroelectric System Dispatching Based on the Daily Load Curve

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Abstract Short-term optimization dispatching of cascaded hydroelectric system with day (or week) cycle is of great value in practical implementation, such as improving grid stability, more power benefits. This study proposes a short-term self-optimization simulation model for cascaded hydroelectric system dispatching, which balances the requirements both of the generation side and the demand side. Three conflicting objectives for the management of hydropower generation are incorporated in the cascaded hydroelectric system. And in this model, the reasonable physical factors are chosen to coordinate the contradiction. According to the characteristics of the self-optimization simulation technique, for example clear physical meaning, more perfect simulation, no dimension limitation, artificial adjustment with the accumulated experience and so on, a new solving idea for this model is set up. And the new operation model is illustrated in the middle reaches of the Chinese Jinsha River, where eight cascades are planned. Considering the different startup time and combinations, the results of the joint operation compared to the single reservoir operation has provided important demonstration for the investment entities, simultaneously the solving efficiency and quality of this model are good for implementing in practical.

Keywords Short-term dispatching · Self-optimization simulation · Multi-objective · Jinsha River

1 Introduction

Energy is a major strategic issue that concerns the overall human and social development. The historical data has attested to a strong relationship between the availability of energy and economic activity. According to recent IEA report (2007), with rapid economic development, the growing rate of global energy demand is about 1.6 % per year, and the total quantity is

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predicted to achieve about $700*10^8$ Joule/Year by 2030 (Pekala et al. 2010). However, at present, more than 80 % production of worldwide primary energy has been coming from combustion of fossil fuels, which some day will inevitably lead to the problem of depletion. And it highlights how vulnerable the energy supply is to political conflict when two oil disruptions of the Middle East happened in the 1970s. Moreover, the problem of environmental pollution resulting from the use of fossil energy is becoming more and more serious. For example, greenhouse gas, acid rain, and particulate matter are all serious threat to human health. The renewable energy is the long-term potential actions for sustainable development, such as solar energy, wind energy, hydropower energy, biomass energy, and geothermal energy. And hydropower, as the most important sustainable energy source, has been a competitive technology for more than a century. It contributes one-fifth of the power generation of the world. In fact, for several OECD countries, more than 50 % share of electricity generation is hydropower, and in some other countries, hydropower is the only domestic energy resource. In a word, comparing to other renewable energy, hydropower plays a more important role in electricity generation.

In China, the continuous increase of energy consumption has become more apparent because of the rapid industrialization, urbanization and modernization. The "Twelve 'Five Year' Electrical Plan in China", has made it clear that hydropower will be placed in the first priority amongst all types of the electricity generation. At present, 213.4GW of the Chinese energy, that is 22.2 %, is from hydropower plants. The hydropower installed capacity will reach 284 GW and 330 GW in 2015 and 2020, respectively. By then, the total hydropower installed capacity in China will be equivalent to the summation of the other top seven countries in the world (Based on data of 2007). The characters of the hydropower system affect the security and economic operation of Chinese power grid, since the features are so rare, complicated, and unique in the world history. In general, most constituents of the Chinese hydropower systems are cascade hydropower stations, and the operation and management of the cascaded hydropower stations is usually a multi-objective problem. So it is becoming more and more significant, urgent and difficult to determine the optimal hydro generation plan in China.

At present, low utilization efficiency and high waste are two outstanding characteristics of the Chinese developed hydropower operation. According to statistics, the electricity reduced per year is up to 20 billion kWh only because of head loss. So researches on the optimal scheduling of the cascaded hydroelectric system should be carried out, which can improve the economic benefits without any additional investment. Medium and long term hydroelectric optimal scheduling generally have certain significance in the planning and macro-guidance because of the random and versatile natural runoff. While short-term optimal scheduling of day (or week) cycle becomes more practical. And it plays an important part in improving grid stability and implementing the optimal benefit of the power generation. Many researchers have focused on the short-term cascaded optimal scheduling for a long time. And lots of optimal technologies have been studied to solve this problem, including dynamic programming (DP) (Zhang 2004), network flow (Oliveiraa and Soaresb 2005), mixed-integer quadratic programing (Catalao and Pousinho 2010), particle swarm optimization (PSO) (Ostadrahimi and Miguel 2012), and differential evolution (DE) (Yuan et al. 2010) etc. Generally, there are some defects of those methods, such as dimensionality difficulty, convergence instability, and algorithm complications. So these methods can't be always suitable for the complex cascaded hydroelectric system while the requirements become more and more.

Actually, all of the short-term scheduling technology can be divided into two categories: optimization and simulation. The optimization method is a kind of mathematical model with the objective functions and constraints. Its optimization process is good for seeking the excellent direction of the overall system. However, the inherent weakness, such as "dimension difficulty" and poor simulation degree can't be ignored. The simulation technology can be viewed as a kind of "impulse response" model. Some input information will produce a corresponding output following the interior predetermined logic judgment. So the external controllability is its dominating character. The advantages of this method are understandable, strong simulative, and adjustable to actual situation and professional experience. However, sometimes it is too entangled in details to grasp the overall goal. But in practical application, people hope the system doesn't only optimize along the overall decision direction, but also can proceed under control. Therefore the self-optimization simulation technology is produced through combining the characteristics of the two methods. O.T.sigvaldason (1976) succeeded in inserting an optimized sub-model into the simulation model, and under controlling the penalty coefficient, simulated different operating strategies of the optimal running. The work was proved to be significant. Lei (1989), with the basic principles of modern control theory, added the links of identification, optimal control and guidance into the simulation process, and then in the east route of South-to-North Water Transfer Project planning, proposed the corresponding self-optimization simulation model and achieved satisfactory results. Li (2000) built the Yellow River upstream cascade water real-time scheduling optimization model using the self-optimization simulation technology, and the results demonstrated that the model was simple and flexible in practice. Afzali et al. (2008) presented a multi-reservoir reliability-based simulation model for the integrated operation of the reservoir system. The models were applied to a hydropower system in Iran as a case-study. Khan and Babel (2012) applied the Reservoir Optimization-Simulation with Sediment Evacuation (ROSSE) model with the aim of minimizing irrigation shortages in the Tarbela Reservoir, Pakistan, and also calculated the suitable values of various GA parameters required to run the model through a sensitivity analysis. Yu (2012), from the point of view that the power output characteristics should be as consistent as the system load characteristics, built models respectively according to two scheduling modes, one of which is the day scheduling mode with the maximum daily generation capacity as its optimization criterion, the other is the concentrated peaking load mode with the maximum peaking capacity as the optimization criterion.

According to the above analysis, the short-term scheduling is of great importance in practice and theory because of its obvious intermediate link position for connecting the mid-long term scheduling and economical operation. This paper aims to develop a practical model for the short-term optimization scheduling of Chinese cascaded hydroelectric system, through coupling the self-optimization simulation technology with the multi-objective ideology. From the point view of the power supply and power demand, it should not only consider the total generating capacity to obtain the whole benefit, but also need to ensure the output process as consistent as the load curve for keeping the power grid safe. Meanwhile the peak generating capacity should be taken into account. So this model is a typical multi-objective decision problem with three objective functions regarded. And the results obtained from the Jinsha River can help generate the desired decision that the short-term self-optimization simulation scheduling model of Chinese cascaded hydroelectric system will be able to not only satisfy the requirements of the power demand parts but also meet the requirements of the supply parts as far as possible.

2 Self-Optimization Simulation Model of Short-Term Cascaded Hydroelectric System Scheduling Based on the Daily Load Curve

2.1 Self-Optimization Simulation Principle

General simulation is a response progress that the simulated output wholly depends on the input elements. The process is revealed in part ① Fig. 1 (dashed line range). But in this way the output is only a natural response because of the immutable and uncontrollable input

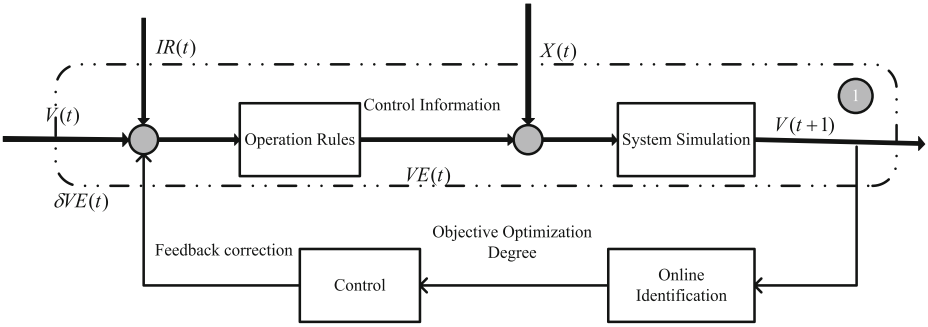

Fig. 1 System simulating and controlling progress

sequence. The only way for obtaining the optimal target is to establish the searching response surface. However, the response surface will be becoming more and more complex with the increasing control system states. Even if at last the optimal result is achieved by this simulation, but it inevitably has wasted a long time for the calculation.

Therefore, it is necessary to seek a controllable simulation structure to change the open-loop control mode to closed-loop (negative feedback) control. When output is retroacted to the input terminal, a simulating control line will be formed automatically with the relative feedback to guide the continuous running. The simulating process won't stop circulating until the simulated results tend to the optimal target. In the reservoir system, since the optimal result controlled is not known, so it is necessary to generate a self-adaptive link with automatic identification, judgment and amendment. A control correction will be generated to guide the simulation system further optimal, when the optimal performance of the simulation control line is identified by the output online. The correction together with system operating rules and other constraints guides the system to proceed more reasonably. As a result, the simulation control line gradually converges to the optimal control line, and simultaneously the simulated results tend to the optimal results as far as possible.

2.2 Self-Optimization Simulation Model

2.2.1 Objective Function

The optimization criteria of the cascaded hydroelectric system should fully meet the requirements of the grid scheduling departments, especially the characteristics of the load curve. Namely the actual output process should be as consistent as the system load instruction process. And it is well known to all that the more peak load taken on, the more positive affection is for the grid system and the generate electricity supplier. Therefore, the maximum peaking power is another optimization criterion. At last it is the maximum generating capacity target through coordinating running program of the flat and valley period. From the above analysis, it's the objective functions are respectively arranged as: the minimum total deviation between the actual power generation process and system load instruction process during scheduling period; maximum cascaded total peaking capacity; maximum cascade total power generation. The formulas are as follows:

$$TD = \min\left\{\sum_{n=1}^{N}\sum_{t=1}^{T}\left(\left(N_{n,t}-FN_{n,t}\right)^2\right)\right\} \tag{1}$$

$$TPE = \max \sum_{n=1}^{N} \sum_{t=1}^{T_P} N_{pn,t} \bullet \Delta t \tag{2}$$

$$TE = \max \sum_{n=1}^{N} \sum_{t=1}^{T} N_{n,t} \bullet \Delta t / 3600 = \sum_{n=1}^{N} \sum_{t=1}^{T} k q_{n,t} H_{n,t} \bullet \Delta t / 3600 \tag{3}$$

Where, *TD* is defined as the total deviation between the power generation process and the system desired process during scheduling period; *TPE* is the total peaking generating capacity of all the peak load period; *TE* is the total generating capacity of the scheduling period; $N_{n,t}$ is the actual output of hydropower n in period t; $FN_{n,t}$ is the power load curve's indicating output of hydropower n in period t; $N_{pn,t}$ is the actual peak-load output of hydropower n in period t; $q_{n,t}$ is the generation flow in period t, whose unit is m^3/s; $H_{n,t}$ is the average power head of hydropower n in period t, whose unit is m; Δt is the length of time period, whose unit is s; k is the output coefficient; T is the total number of time periods; N is the total number of cascade hydropower stations.

Note: abnormal extra disposable water is the abandoned water while the reservoir level is below the normal water level (or flood control level) or the power plants' output has not reached the expected output.

2.2.2 Constraint Conditions

(1) Reservoir water balance constraints:

$$V_n(t+1) = V_n(t) + \left(Q_{n,R}(t) - Q_{n,C}(t) - Q_{n,L}(t)\right) \bullet \Delta T \tag{4}$$

$$Q_{n,R}(t) = I_{n,R}(t) + e^{\gamma} \bullet \left(s_{n-1,q}(t-\tau) + q_{n-1,f}(t-\tau)\right) \tag{5}$$

$$Q_{n,C}(t) = s_{n,q}(t) + q_{n,f}(t) \tag{6}$$

Where, $V_n(t)$, $V_n(t+1)$ represent the reservoir water volume respectively for the beginning and end time of period t; $Q_{n,R}(t)$, $Q_{n,C}(t)$, $Q_{n,L}(t)$ stand for separately inflow, outflow, lost flow of hydropower n in period t (evapotranspiration, seepage water losses and so on); $s_{n-1,q}(t-\tau)$, $q_{n-1,f}(t-\tau)$ are the disposable flow and the generation flow respectively that are from the reservoir $n-1$ to reservoir n in the period $t-\tau$; τ is the time that the stream lasts from the reservoir $n-1$ to reservoir n; $s_{n,q}(t)$, $q_{n,f}(t)$ respectively represent the disposable flow and the generation flow of reservoir n in period t; ΔT is the length of calculating period; e^{γ} is the flattening coefficient, for which γ is a change parameter. In general, e^{γ} and τ will take on different values with the different connections of the cascade hydropower stations group.

(2) Reservoir node water balance constraints:

$$Q_{n+1,C}(t) = Q_{n,C}(t) + Q_{n,R}(t) - Q_{n,U}(t) - Q_{n,L}(t) + Q_{n,T}(t-\tau) \tag{7}$$

Where, $Q_{n+1,C}(t)$ is the outflow of reservoir $n+1$ within period t; $Q_{n,C}(t)$ is the outflow of reservoir n within period t; $Q_{n,R}(t)$ indicates the interval water flow between the reservoir n and reservoir $n+1$ within period t; $Q_{n,U}(t)$ represents the demanded water flow of hydropower n within period t; $Q_{n,L}(t)$ is interval water loss flow of reservoir n within period t; $Q_{n,T}(t-\tau)$ represents the withdrawal water flow of reservoir n within period $t-\tau$, that is, the withdrawal water on agriculture, industry, life and so on of the above node, will be considered as the inflow runoff of next node storage considerations. It can select the corresponding coefficient method to determine the value according to the task of water supply and the different wet, normal, dry season.

(3) Reservoir storage capacity constraints (or water level constraints):

$$V_{n,\min}(t) \le V_n(t) \le V_{n,\max}(t) \tag{8}$$

Where: $V_{n,min}(t)$ is the minimum volume allowed of hydropower n in period t, and generally is the dead capacity; $V_{n,max}(t)$ is the maximum volume allowed of hydropower n in period t, and is generally the corresponding capacity of normal water level, but in flood season, is the corresponding capacity of the flood protection limited water level.

(4) Hydropower station machine flow constraints:

$$Q_{m,M,\min}(t) \le Q_{m,M}(t) \le Q_{m,M,\max}(t) \tag{9}$$

$Q_{m,M,min}(t)$, $Q_{m,M,max}(t)$ represent the minimum and maximum machine flow of hydropower m in period t, respectively.

(5) Hydropower station output constraints:

$$N_{m,\min}(t) \le N_m(t) \le N_{m,\max}(t) \tag{10}$$

$N_{m,M,min}(t)$, $N_{m,M,max}(t)$ represent respectively the minimum and maximum allowable output of hydropower m in period t.

(6) Hydropower station discharge flow constrains:

$$Q_{m,C,\min}(t) \le Q_{m,C}(t) \le Q_{m,C,\max}(t) \tag{11}$$

$Q_{m,C,min}(t)$, $Q_{m,C,max}(t)$ represent the minimum and maximum outflow of hydropower m in period t respectively.

(7) Reservoir station boundary condition constraint:

$$Z_n(t) = Z_b \quad Z_n(t+1) = Z_e \tag{12}$$

$Z_n(t)$ is the reservoir level at the beginning of the scheduling period of Reservoir n, $Z_n(t+1)$ is the reservoir level at the end of the scheduling period of Reservoir n.

(8) Variable nonnegative constraints.

3 The Solving Technique for Self-Optimization Simulation Model

3.1 Solving Ideas and the Block Diagram

According to the theory of multi-objective decision making, this paper selects coordination factors with the actual physical background to convert the multi-objective problem to a single objective problem. Firstly it is to analyze the objective function of the minimum cascade hydropower stations' total deviation. When the power generation process in each scheduling calculation period is reconciled with the load curve generation, the *TD* target value will be zero with condition that there is no abnormal extra disposable water, to the contrary, *TD* will obviously be bigger than zero. Secondly, the objective function of the maximum peaking power is considered. In order to coordinate the two optimization criteria, a weighting factor $W_{n,t}$ with physical meaning is introduced. The transforming form is as follows:

$$\min\left\{\sum_{n=1}^{N}\sum_{t=1}^{T} W_{n,t}\left(N_{n,t}-FN_{n,t}\right)^2\right\} \tag{13}$$

From the point view of taking on larger peak and valley load, the $W_{n,t}$ selected is taken as the punishment factor of the unit output which actually maintains a certain ratio to $FN_{n,t}$. When $FN_{n,t}$ represents the output of peak load periods,, $W_{n,t}$ is necessarily large according to its proportional relationship. Hence, under this condition the aim to meet the minimum *TD* objective, only can be achieved by choosing the strategy that $(N_{n,t}\text{-}FN_{n,t})$ is relatively smaller. And it works the other way as well. Finally it is to consider the objective function of cascade hydropower total generating capacity with taking the system specified load as a lower limit to fulfill.

$$\max\left\{\begin{array}{l} W_1\left[\sum_{n=1}^{N}\left(\sum_{t=1}^{m} C_{pn,t}\left(N_{pn,t}-FN_{n,t}\right)+\sum_{t=m+1}^{T} C_{ln,t}\left(FN_{n,t}-N_{ln,t}\right)\right)\right] \\ +W_2\left[\sum_{n=1}^{N}\left(\sum_{t=1}^{m} C_{Pn,t}\left(N_{Pn,t}\bullet\Delta t-FE_{n,t}\right)+\sum_{t=m+1}^{T} C_{Ln,t}\left(N_{Ln,t}\bullet\Delta t-FE_{n,t}\right)\right)\right] \end{array}\right\} \tag{14}$$

Where, $[1,m]$ is the peak load stage; $[m+1,T]$ is the valley stage; W_1, W_2 represent the weight for the hydropower peaking power and power generation respectively; $C_{pn,t}$ is the unit output reward (punishment) when the power generation is increased (decreased) in the peak period; $C_{ln,t}$ is the unit output reward (punishment) when the power generation is decreased (increased) in the valley period; $C_{pn,t}$, $C_{ln,t}$ are both larger than zero; $FE_{n,t}$ is the generated output for each period according to the system specifying output process line; $C_{Pn,t}$ is the reward or supply price in peak period when hydropower station adds the unit output; $C_{Ln,t}$ is the reward or supply price in valley period when hydropower station adds the unit output. In order to consider the three objectives, the coordination factors usually are chosen as the following:

$$C_{pn,t}=FN_{n,t}/\max\left\{FN_{n,i}\middle|i\in[1,T]\right\}\ or\ C_{pn,t}=FN_{n,t}t\in[1,m] \tag{15}$$

$$C_{ln,t}=FN_{n,t}/\max\left\{FN_{n,i}\middle|i\in[1,T]\right\}\ or\ C_{ln,t}=FN_{n,t}t\in[m+1,T] \tag{16}$$

$$C_{Pn,t} = FE_{n,t} / \sum_{i=1}^{T} FE_{n,i} \ or \ C_{Pn,t} = FE_{n,t} t \in [1, m] \tag{17}$$

$$C_{Ln,t} = FE_{n,t} / \sum_{i=1}^{T} FE_{n,i} \ or \ C_{Ln,t} = FE_{n,t} t \in [m+1, T] \tag{18}$$

Supposing: W_1=W_2=1,$C_{pn,t}$+$C_{Pn,t}$=$FN_{n,t}$,$C_{ln,t}$+$C_{Ln,t}$=$FN_{n,t}$, then the objective function can be simplified to the following form:

$$\max \sum_{t=1}^{T} FN_{n,t} \left(\sum_{n=1}^{N} \left(N_{n,t} - FN_{n,t} \right) \right) \tag{19}$$

The basic solving idea is indicated as follows. First step: considering the influence factors, such as reservoir inflow forecasted, water supply plan, water propagation, water loss and so on, the calculation method can be described as the direction is top to down (downstream direction) and the calculation period is from the end to the beginning (anticlockwise timing). The purpose is to deduce the minimum and maximum controlling water level line for each period and reservoir. Second step: the output value *N*, whose normalizing ratio is *1*, is assumed as the installed capacity. The other daily output values can be figured out based on the load curve ratio calculated and the installed capacity presumed. Therefore, the initial output line comes into being. Third step: according to the process line of initial output, the system starts simulating and running with downstream direction (the direction is top to down) and clockwise timing. Then it identifies the reservoir end state. If the water level of this period meets the appointed limits, the system moves on to the next period process. If not, the running process of this period will be simulated again with a feedback correction. The simulation time doesn't go to the next period until the identified water level of this period can fulfill the assumed requirements. At the end of the scheduling period, it's time to identify the final water level and the abnormal extra disposable water. The system starts simulating a new cycle with the output feedback correction formed till the end states of all reservoirs are satisfied the presumed requirements. Finally, it goes to identify the cascade total target. The specific steps are shown in the block diagram in Fig. 2.

3.2 Solving Steps

3.2.1 The Controlling Equations of the Maximum and Minimum Reservoir Water Level

According to the forecasting inflow and the requirements of the water supply in the control area, the controlling lines of the maximum and minimum water level for each period and reservoir is deduced through the calculation method whose direction is top to down (downstream direction) and calculation period is from the end to the beginning (anticlockwise timing). The calculation equations are as follows:

$$VLL_n(t) = VL_n(t+1) - \sum_{i=k(n-1)+1}^{k(n)} \left[Q_{i,R}(t) - Q_{i,U}(t) + Q_{i,T}(t-\tau) - Q_{i,L}(t) \right] \bullet \Delta t + Q_{n,C,\min}(t) \cdot \Delta t \tag{20}$$

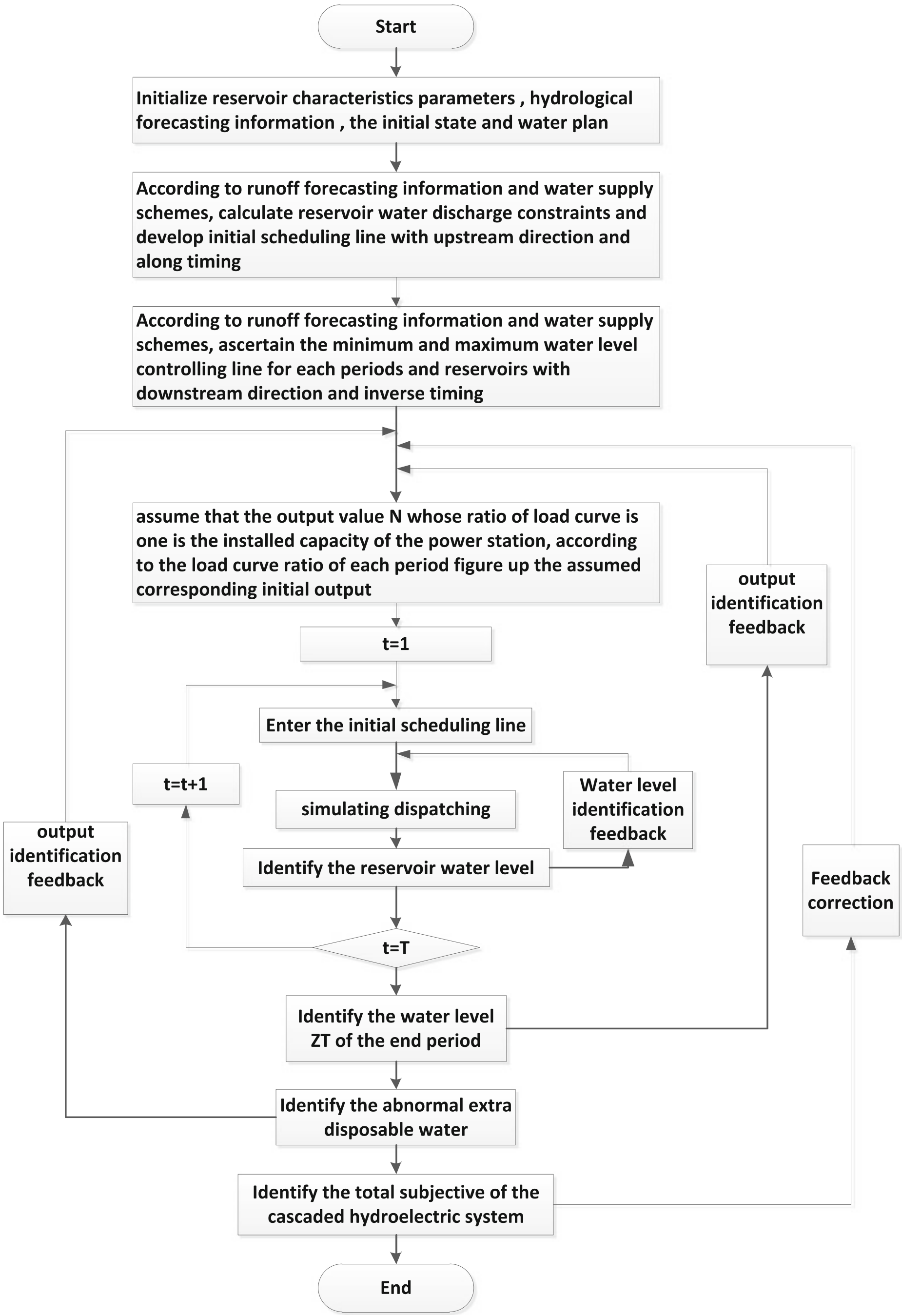

Fig. 2 Schematic of the self-simulation optimization model

$$VL_n(t) = \min\left\{VLL_n(t), V_{n,\min}(t)\right\} \tag{21}$$

$$VHL_n(t) = VH_n(t+1) - \sum_{i=k(n-1)+1}^{k(n)} \left[Q_{i,R}(t) - Q_{i,U}(t) + Q_{i,T}(t-\tau) - Q_{i,L}(t)\right] \dot{}\Delta t + Q_{n,C,\max}(t) \dot{}\Delta t \tag{22}$$

$$VH_n(t) = \min\left\{VHL_n(t), V_{n,\max}(t)\right\} \tag{23}$$

Where: $VL_n(t)$ is the corresponding minimum capacity of the reservoir n in period t; the $VH_n(t)$ is the corresponding maximum capacity of the reservoir n in period t; $Q_{n,R}(t)$, $Q_{n,C}(t)$ can be gotten from the formulas (5) and (6), respectively; $k(n)$ represents the total rivers of the reservoir n above.

3.2.2 Reservoir Water Supply Constraints and Initial Scheduling Line Calculation Model

In order to determine the lower constraints limits of the reservoir water supply, it adopts upstream direction and clockwise timing. At first it decides the running process clockwise timing on the condition of meeting its own water supply. Then it calculates the minimum complement water in accordance with the water shortage, together with the other minimum requirements. Through the downstream direction simulation, the new water replenishment requirements are coupled back when the node of lower reaches adjusts its runoff process. Water shortage computing model of the two adjacent reservoirs is as follows:

$$Q_{n,A}(t) = Q_{n,S}(t) + \Delta Q_n(t) \tag{24}$$

$$Q_{n,S}(t) = Q_{n,R}(t) - Q_{n,U}(t) - Q_{n,L}(t) \tag{25}$$

$$\Delta Q_{n+1}(t) = \begin{cases} 0 & (n=0); \\ Q_{n,T}(t--\tau) & Q_{n,A}(t) \le 0; \\ Q_{n,T}(t--\tau) + Q_{n,A}(t) & Q_{n,A}(t) > 0; \end{cases} \tag{26}$$

$$Q_{n,TA}(t) = \sum_{i=k(n)+1}^{k(n)+j(n)} Q_{i,A}(t) \tag{27}$$

$$Q_{n,C,\min}(t) = \max\left\{Q_{n,TA}(t), Q_{n,M,\min}(t)\right\} \tag{28}$$

Based on the drainage lower limit constraints, the initial schedule line determined is as follows:

$$Q_{n,C,begin}(t) = \min\left\{Q_{n,C,\min}(t), Q_{n,C,\max}(t)\right\} \tag{29}$$

Where: $Q_{n,R}(t)$, $Q_{n,C}(t)$ as shown can be got from the formulas (5) and (6), respectively; $Q_{n,TA}(t)$ is the minimum replenishment water of reservoir n in period t; $Q_{n,C,min}(t)$ is the discharge water low limit of reservoir n in period t; $Q_{n,C,begin}(t)$ represents the beginning scheduling value of reservoir n in period t; $k(n)$ represents the total rivers of the reservoir n

above; *j(n)* is the total direct supply rivers of reservoir *n*; remaining symbols are the same meaning as above.

3.2.3 The Calculating Method of the Reservoir Initial Output Curves

In order to compare conveniently, the first step is to normalize the output values of the load curve given by the power grid. Then the output value N whose ratio is 1 is assumed as the installed capacity, namely the day maximum output. Finally, the other corresponding initial outputs are figured up according to the load curve ratio of each period.

3.2.4 Reservoir Operation Simulation Model

The system proceeds with the downstream direction and the clockwise timing period by period. The simulating equations of the calculation progress are as follows:

$$V_n(t+1) = V_n(t) + \left[\sum_{i=k(n-1)+1}^{k(n)} \left(Q_{i,R}(t) - Q_{i,U}(t) - Q_{i,L}(t)\right) - Q_{n,C}(t)\right] \bullet \Delta T \qquad (30)$$

$$N_n(t) = \eta(n) \bullet Q_{n,M}(t) \bullet H_{n,ave}(t) \qquad (31)$$

$$Q_{n,M}(t) = \min\left\{Q_{n,C}(t), Q_{n,M,\max}(t)\right\} \qquad (32)$$

$$H_{n,ave}(t) = H_{n,up}(t) - H_{n,down}(t) - \Delta H_n(t) \qquad (33)$$

Where: $Q_{n,R}(t)$, $Q_{n,C}(t)$ can be gotten from the formulas (5) and (6), respectively; *k(n)* represents the total rivers of the reservoir *n* above; $\eta(n)$ is the output coefficient of power station *n*; $H_{n,ave}(t)$is the average power head of power station *n*; $H_{n,up}(t)$, $H_{n,down}(t)$ represent respectively the upstream and downstream average water level of reservoir *n* in period *t*; $\Delta H_n(t)$ is the head loss of power station *n*; $Q_{n,M}(t)$ is the power flow of power station *n* in period *t*.

3.2.5 The Online Identification of the Feedback System

According to the control theory and the principle of feedback correction, this paper applies the four layer identification feedback structures to solve the self-optimization simulation model established. In each layer a corresponding correction is coupled back through identifying the specified scalar. At last the satisfying solving scheme is generated step by step with iterating and looping. The feedback structure is as Fig. 3.

4 Case Study

The Jinsha River is the upper reaches of the Yangtze River. It starts from Yushu of Qinghai Province to Yibin of Sichuan Province. The whole length is 2291 km, catchment area is 362000 km^2, the river falls over 4000 m, and the multi-annual average discharge is about

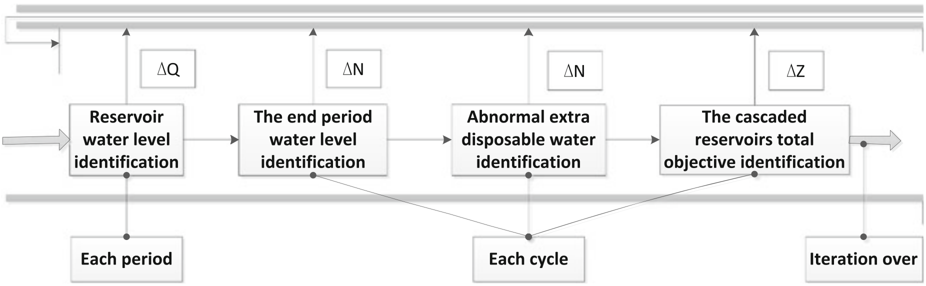

Fig. 3 Schematic of the feedback structure

4920 m^3/s (2010). At present, the 1500 km long middle and lower sections of the mainstream from Shigu to Yibin is planned and developed for the Cascade hydropower exploitation (CHE) base at Jinsha River. The total installed capacity of the base is 51395 MW and its annual generating capacity is 248.58TWh (2008). It is China's largest CHE base and the main supply for the "West–east Electricity Transfer Project". The 700 km-long section of mainstream from Shigu to Panzhihua is the middle reaches of the Jinsha River, where 8 cascades (Fig. 4) are planned with the installed capacity of 20580 MW. And they are charged by four investments.

The six power plants of the lower reaches are to be completed at first because Longpan Hydropower Station and Liangjiaren are now in the demonstration phase. So how to manage the operation mode of the six stage cascade hydropower stations previously formed is a serious problem The regulation performances of the six power stations are all poor, for their regulating periods are only daily or weekly. And their investment subjects are not unified. So it is very necessary to compare the benefit of the separated to the combined operation with different combinations and different production phases, which is the important

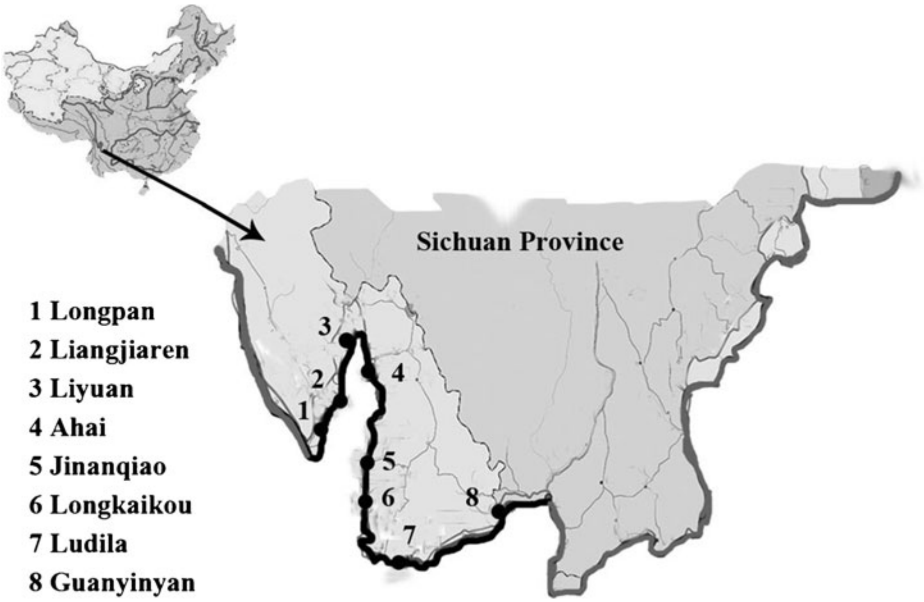

Fig. 4 Overview map of the Jinsha river planning

demonstration for realizing the water resources optimal allocation. This paper at first generalizes the real reservoir system and each reservoir is selected as the compute nodes. Then through the analysis of the runoff data, three representative years: wet year, normal year, dry year are chosen, and the system simulates and schedules with the typical daily runoff and the corresponding daily load curves of each month of the chosen years. There are three typical days selected of each month, one is the day that the daily average flow is most close to the monthly average, and the other 2 days are the minimum and maximum daily average flow, respectively.

The typical daily load curves predicted of Yunnan in 2015 (wet season and dry season) are chosen to use in this article. At the same time, the distances between the cascade hydropower stations are small because of the connected type connection. And the upstream power station discharge can spread rapidly to the downstream station. So the coefficients mentioned above are confirmed as the following $\tau=0$, $\gamma=0$, as a result the flatting coefficient $e^{\gamma}=1$.

Before the leading power (Longpan Hydropower Station) being put into operation, the six power stations have been divided into five scheduling combinations because of their different accomplished and operating time. The first is the separated and combined operation of Jinanqiao, Longkaikou (combination one); the second is the separated and combined operation of Jinanqiao, Longkaikou, Ludila (combination two); the third is the separated and combined operation of Ahai, Jinanqiao, Longkaikou, Ludila (combination three); the forth is the separated and combined operation of Liyuan, Ahai, Jinanqiao, Longkaikou, Ludila (combination four); the fifth is the separated and combined operation of Liyuan, Ahai, Jinanqiao, Longkaikou, Ludila, Guanyinyan (combination five). At last it is to compare the benefit of the separated operation with the combined for the each combination in different phases.

5 Results and Discussion

With the self-optimization and simulation model and the special solving technique, the benefits of the separated operation were compared to the combined operation for each combination in different production periods. This paper selects combination five to analyze, and the results are as follows. Noting: the daily power generation in the table actually is an average data of each month.

Viewing on the data of the three typical years in Tables 1, 2 and 3, the monthly total generating capacity of each reservoir is improved to a certain extent when the results of the combined scheduling are compared to the separated scheduling's. The relatively large growth is from February to April, because the 5 months belong to water supply periods with less incoming water. The scheduling compensation and coordination of the electric quantity and water volume among the cascade reservoirs are reflected better, especially for the combined operation. The generation power from July to October of wet year has no difference between the separated operation and the combined operation, for the incoming water in flood season of wet year is so large that the installed capacity is almost generated by the reservoirs. Besides, the monthly power generation growth of normal year and dry year is larger than the wet year. The main reason is that the reservoir inflow of the two typical years is relatively smaller than the wet year, so the effect of the combined dispatching is more obvious. The cascade total generating capacity analysis chart is shown in Table 4 and Figs. 5, 6 and 7:

According to the tables and figures, the monthly changing tendency of cascade total generating capacity is basically consistent with the single reservoir, and each monthly generation of the three typical years has a certain growth. Actually, there is a direct

Table 1 The daily power generation of wet year (combination 5)

Name		Wet year												
		Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Ave
Li Yuan	Sep	3160	4454	4454	5669	5568	2829	1892	1440	1259	1265	1591	2185	2981
	Com	3160	4454	4454	5669	5568	2829	1892	1440	1259	1265	1591	2185	2981
	Grow	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
Ahai	Sep Opr	2716	4195	3817	4804	4804	2597	1858	1367	1166	1139	1409	1904	2648
	Com	2724	4195	3817	4804	4804	2608	1870	1374	1170	1146	1412	1912	2653
	Grow	0.29 %	0.00 %	0.00 %	0.00 %	0.00 %	0.42 %	0.65 %	0.51 %	0.34 %	0.61 %	0.21 %	0.42 %	0.19 %
Jin anqiao	Sep Opr	3624	5765	5544	5765	5765	3468	2513	1841	1565	1526	1879	2559	3485
	Com	3641	5765	5544	5765	5765	3489	2534	1859	1581	1543	1896	2577	3497
	Grow	0.47 %	0.00 %	0.00 %	0.00 %	0.00 %	0.61 %	0.84 %	0.98 %	1.02 %	1.11 %	0.90 %	0.70 %	0.35 %
Long kaikou	Sep Opr	2268	4326	4182	4326	4326	2209	1600	1168	991	961	1182	1588	2427
	Com	2284	4326	4182	4326	4326	2226	1619	1186	1009	978	1199	1605	2439
	Grow	0.71 %	0.00 %	0.00 %	0.00 %	0.00 %	0.77 %	1.19 %	1.54 %	1.82 %	1.77 %	1.44 %	1.07 %	0.48 %
Ludila	Sep Opr	2811	5049	4838	5049	5049	2785	2080	1494	1254	1204	1473	1988	2923
	Com	2825	5049	4838	5049	5049	2809	2102	1514	1274	1219	1491	1996	2935
	Grow	0.50 %	0.00 %	0.00 %	0.00 %	0.00 %	0.86 %	1.06 %	1.34 %	1.59 %	1.25 %	1.22 %	0.40 %	0.40 %
Guan yinyan	Sep Opr	3817	6889	6347	6871	7213	3891	2963	2097	1743	1655	2013	2691	4016
	Com	3841	6889	6347	6871	7213	3929	2999	2131	1777	1684	2040	2703	4035
	Grow	0.63 %	0.00 %	0.00 %	0.00 %	0.00 %	0.98 %	1.21 %	1.62 %	1.95 %	1.75 %	1.34 %	0.45 %	0.49 %
Total	Sep Opr	18396	30678	29182	32484	32725	17779	12906	9407	7978	7750	9547	12915	18479
	Com	18475	30678	29182	32484	32725	17890	13016	9504	8070	7835	9629	12978	18539
	Grow	0.43 %	0.00 %	0.00 %	0.00 %	0.00 %	0.62 %	0.85 %	1.03 %	1.15 %	1.10 %	0.86 %	0.49 %	0.32 %

Table 2 The daily power generation of normal year (combination 5)

Name		Normal year												
		Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Ave
Li Yuan	Sep	3249	4454	4488	5762	3816	2180	1305	1059	955	990	1252	2125	2636
	Com	3249	4454	4488	5762	3816	2180	1305	1059	955	990	1252	2125	2636
	Grow	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
Ahai	Sep Opr	2838	4491	4505	4804	3437	2012	1244	1002	903	923	1085	1867	2426
	Com	2849	4491	4505	4804	3449	2024	1249	1010	910	930	1091	1877	2432
	Grow	0.39 %	0.00 %	0.00 %	0.00 %	0.35 %	0.60 %	0.40 %	0.80 %	0.78 %	0.76 %	0.55 %	0.54 %	0.27 %
Jin anqiao	Sep Opr	3809	5765	5765	5765	4589	2725	1677	1347	1212	1239	1445	2488	3152
	Com	3826	5765	5765	5765	4612	2748	1690	1363	1230	1255	1459	2530	3167
	Grow	0.45 %	0.00 %	0.00 %	0.00 %	0.50 %	0.84 %	0.78 %	1.19 %	1.49 %	1.29 %	0.97 %	1.69 %	0.48 %
Long kaikou	Sep Opr	2383	4326	4326	4326	2900	1718	1064	853	773	787	907	1544	2159
	Com	2400	4326	4326	4326	2922	1737	1079	872	789	803	926	1561	2172
	Grow	0.71 %	0.00 %	0.00 %	0.00 %	0.76 %	1.11 %	1.41 %	2.23 %	2.07 %	2.03 %	2.09 %	1.10 %	0.62 %
Ludila	Sep Opr	3186	5049	5048	5049	3682	2201	1364	1094	990	1002	1108	1971	2645
	Com	3201	5049	5053	5050	3713	2227	1381	1113	1008	1019	1125	1979	2660
	Grow	0.47 %	0.00 %	0.10 %	0.02 %	0.84 %	1.18 %	1.25 %	1.74 %	1.82 %	1.70 %	1.53 %	0.41 %	0.55 %
Guan yinyan	Sep Opr	4298	6847	7163	7087	4831	3052	1911	1528	1375	1387	1512	2669	3638
	Com	4328	6847	7168	7089	4872	3092	1943	1561	1408	1417	1539	2680	3662
	Grow	0.70 %	0.00 %	0.07 %	0.03 %	0.85 %	1.31 %	1.67 %	2.16 %	2.40 %	2.16 %	1.79 %	0.41 %	0.65 %
Total	Sep Opr	19763	30932	31295	32793	23255	13888	8565	6883	6208	6328	7309	12664	16657
	Com	19853	30932	31305	32796	23384	14008	8647	6978	6300	6414	7392	12752	16730
	Grow	0.46 %	0.00 %	0.03 %	0.01 %	0.55 %	0.86 %	0.96 %	1.38 %	1.48 %	1.36 %	1.14 %	0.69 %	0.44 %

Table 3 The daily power generation of dry year (combination 5)

Name		Dry year												
		Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Ave
Li Yuan	Sep	3817	2855	3392	3946	2166	1452	1016	834	775	822	1075	2761	2076
	Com	3817	2855	3392	3946	2166	1452	1016	834	775	822	1075	2761	2076
	Grow	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
Ahai	Sep Opr	3080	2585	3061	3590	1920	1281	918	766	723	741	892	2207	1814
	Com	3091	2594	3070	3601	1928	1286	925	772	727	746	897	2217	1821
	Grow	0.36 %	0.35 %	0.29 %	0.31 %	0.42 %	0.39 %	0.76 %	0.78 %	0.55 %	0.67 %	0.56 %	0.45 %	0.41 %
Jin anqiao	Sep Opr	4079	3921	4677	4809	2558	1711	1227	1026	967	989	1184	2935	2507
	Com	4097	3943	4699	4834	2577	1726	1243	1043	986	1003	1199	2955	2525
	Grow	0.44 %	0.56 %	0.47 %	0.52 %	0.74 %	0.88 %	1.30 %	1.66 %	1.96 %	1.42 %	1.27 %	0.68 %	0.74 %
Long kaikou	Sep Opr	2538	2472	2955	3040	1612	1077	1219	653	619	629	742	1807	1614
	Com	2554	2490	2973	3059	1628	1092	1236	670	635	643	758	1829	1631
	Grow	0.63 %	0.73 %	0.61 %	0.63 %	0.99 %	1.39 %	1.39 %	2.60 %	2.58 %	2.23 %	2.16 %	1.22 %	1.05 %
Ludila	Sep Opr	3018	3152	3749	3848	2026	1334	972	819	783	783	915	2265	1972
	Com	3034	3181	3780	3881	2047	1354	990	837	802	795	932	2277	1993
	Grow	0.53 %	0.92 %	0.83 %	0.86 %	1.04 %	1.50 %	1.85 %	2.20 %	2.43 %	1.53 %	1.86 %	0.53 %	1.04 %
Guan yinyan	Sep Opr	3973	4150	4933	5097	2639	1825	1341	1134	1083	1070	1215	2960	2618
	Com	4004	4193	4975	5141	2672	1859	1375	1165	1116	1095	1243	2976	2651
	Grow	0.78 %	1.04 %	0.85 %	0.86 %	1.25 %	1.86 %	2.54 %	2.73 %	3.05 %	2.34 %	2.30 %	0.54 %	1.25 %
Total	Sep Opr	20505	19135	22767	24330	12921	8680	6693	5232	4950	5034	6023	14935	12600
	Com	20597	19256	22889	24462	13018	8769	6785	5321	5041	5104	6104	15015	12697
	Grow	0.45 %	0.63 %	0.54 %	0.54 %	0.75 %	1.03 %	1.37 %	1.70 %	1.84 %	1.39 %	1.34 %	0.54 %	0.76 %

Noting: Sep represents separated operation; Com represents combined operation; Grow represents the growth rate between the combined operation and the separated operation; Ave represents the average value

Table 4 Total generating capacity of the cascade system (combination 5)

Name	Wet year			Normal year			Dry year		
	Sep	Com	Growth	Sep	Com	Growth	Sep	Com	Growth
Jun	18396	18475	0.43 %	19763	19853	0.46 %	20505	20597	0.45 %
Jul	30678	30678	0.00 %	30932	30932	0.00 %	19135	19256	0.63 %
Aug	29182	29182	0.00 %	31295	31305	0.03 %	22767	22889	0.54 %
Sep	32484	32484	0.00 %	32793	32796	0.01 %	24330	24462	0.54 %
Oct	32725	32725	0.00 %	23255	23384	0.55 %	12921	13018	0.75 %
Nov	17779	17890	0.62 %	13888	14008	0.86 %	8680	8769	1.03 %
Dec	12906	13016	0.85 %	8565	8647	0.96 %	6693	6785	1.37 %
Jan	9407	9504	1.03 %	6883	6978	1.38 %	5232	5321	1.70 %
Feb	7978	8070	1.15 %	6208	6300	1.48 %	4950	5041	1.84 %
Mar	7750	7835	1.10 %	6328	6414	1.36 %	5034	5104	1.39 %
Apr	9547	9629	0.86 %	7309	7392	1.14 %	6023	6104	1.34 %
May	12915	12978	0.49 %	12664	12752	0.69 %	14935	15015	0.54 %
Ave	18479	18539	0.32 %	16657	16730	0.44 %	12600	12697	0.76 %

relationship between the cascade total generating capacity and the incoming water. In February, the inflow is the least of the three typical kind years, so the growth of the cascaded total generating capacity is the largest with the combined operation of cascade reservoirs.

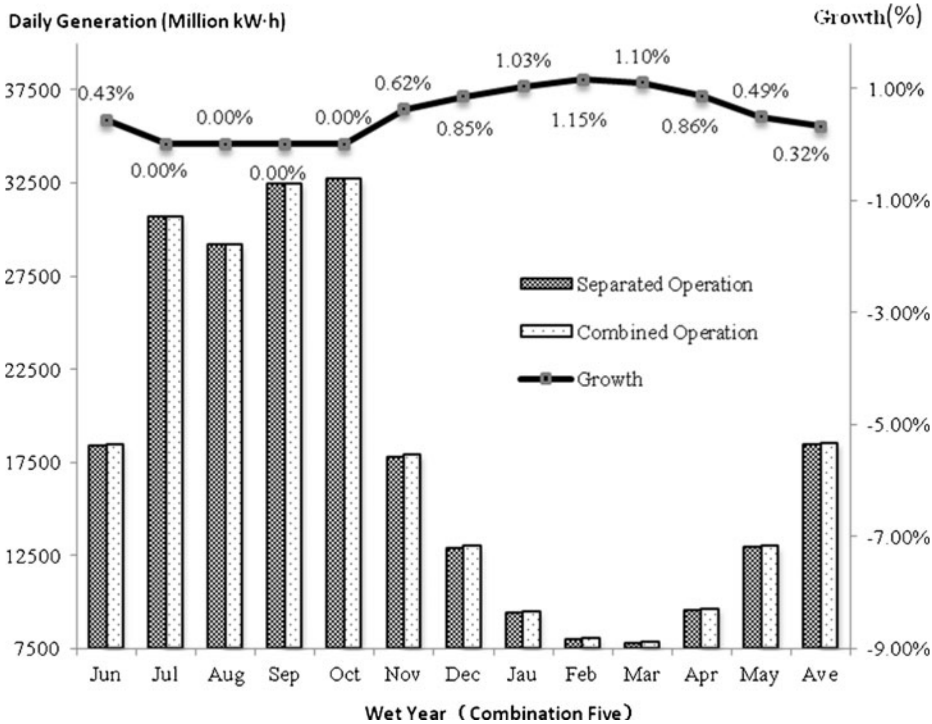

Fig. 5 Total generating capacity comparing the separated with combined operation (wet year)

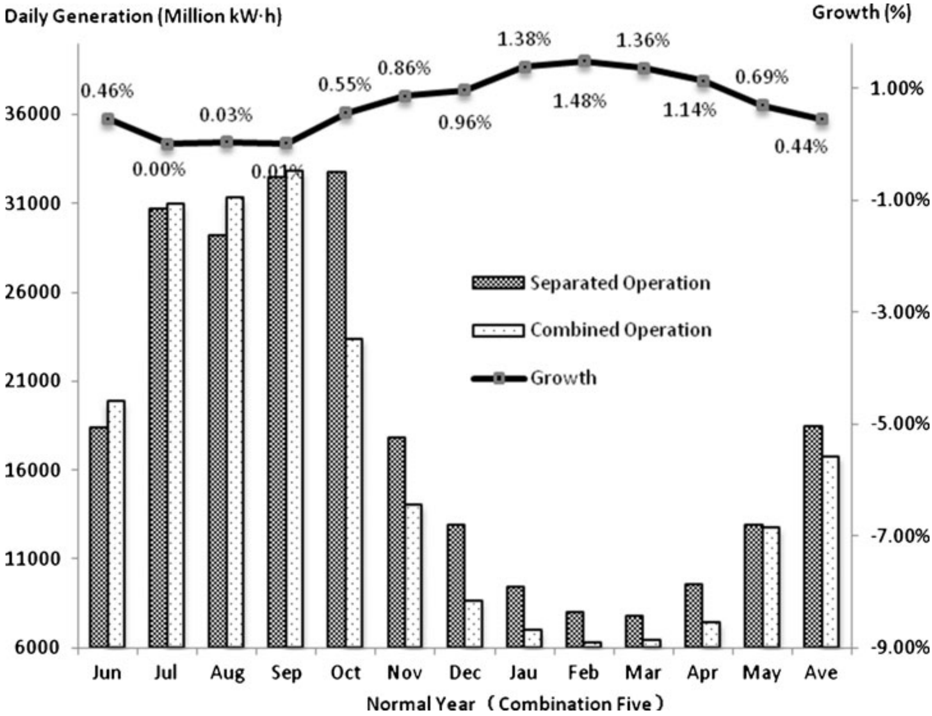

Fig. 6 Total generating capacity comparing the separated with combined operation (normal year)

From the whole view, the incoming water of the dry year and normal year is certainly less than the wet year, therefore their increasing rate of the total generating capacity is much larger compared to the wet year, and the largest growth obviously happens in the dry year. But to the total quantities of the cascaded generating capacity, there is no doubt that the number of the wet year is the largest, because relatively adequate incoming water will inevitably generate more power. The analysis of the total power generation capacity data for each combination and each typical year is listed in Table 5.

From the perspective of the overall analysis of the data, for the five combinations of different startup time, when the results of the combined operation are compared to the separate operation's, whether is in wet year, or normal year, or dry year, all the total power generation capacity has increased in some degree a. And the average percentage growth of the daily power generation is between 0.03 % and 0.76 %. The main reason can be described as follows: when it is in the separated operation, the discharging process of the upstream power station cannot be predicted accurately by the lower station, so appropriate storage is reserved in order to avoid the unnecessary abandoned water; then a problem comes into being that the total quantity of the power generation has been reduced because of the relative low running water head; but when it is of the combined operation the cascaded system following the "daily load scheduling model", the discharge process of the upstream station is able to be used by the downstream power station directly since it is consistent with the daily load curve as far as possible; as a result the total power production has been increased for the station can keep operating with high head in most periods.

From the point of view of the five combinations in different production period, it can be deduced from comparing the combined operation to the separated operation, no matter in

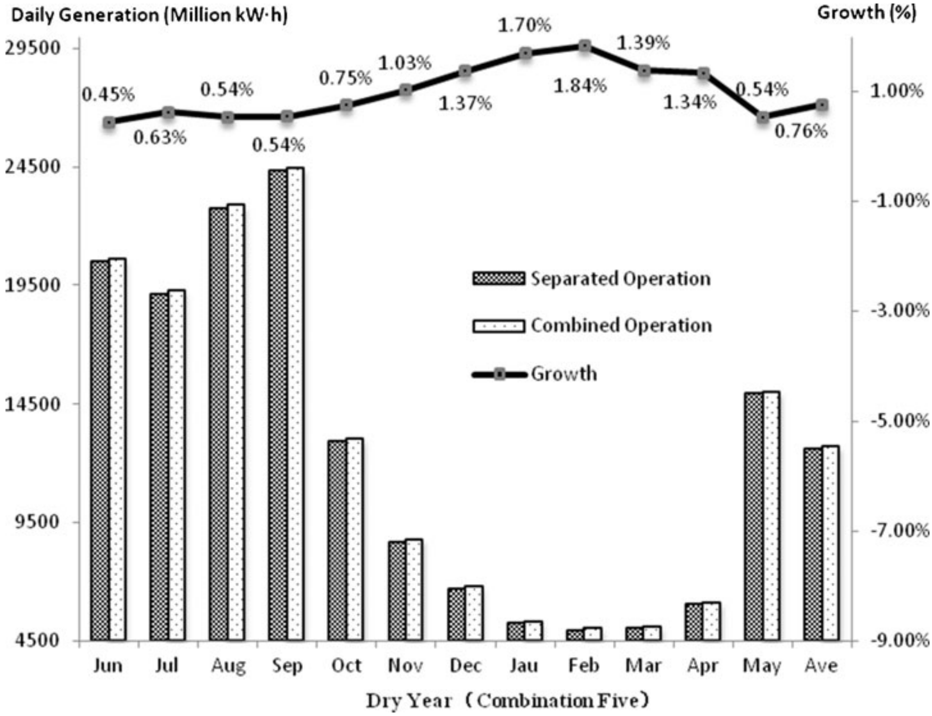

Fig. 7 Total generating capacity comparing the separated with combined operation (dry year)

which typical year, the growth degree of the output is increased with the added number of the cascade hydropower group. Because more reservoirs in the cascaded system mean more room to be adjusted, so the lower station of the combined operation runs with relative high water head. Viewing on the data of the three typical years, no matter which combination it is, the generation growth of the combined operation in dry year is all higher than in wet and normal year. As there are more scheduling periods with the expected output in wet and

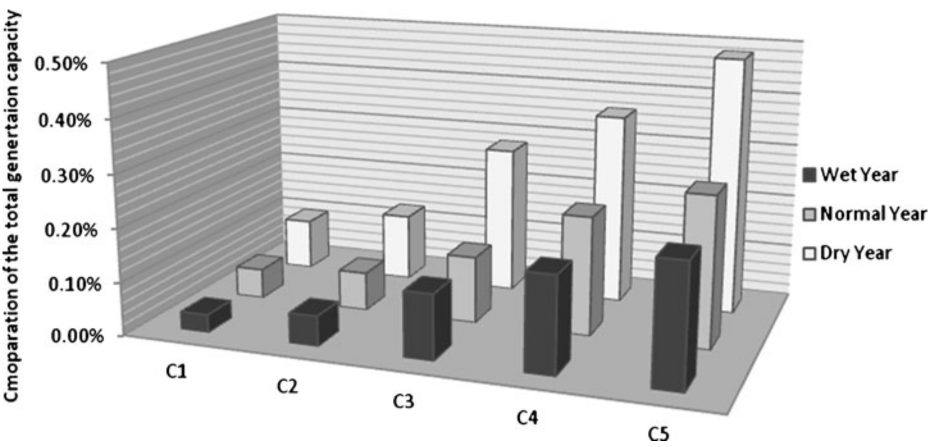

Fig. 8 The growth of total power generation capacity for each combination and each typical year

Table 5 Total power generation capacity for each combination and each typical year

Name		Wet year			Normal year			Dry year		
		Sep	Com	Growth	Sep	Com	Growth	Sep	Com	Growth
C1	Jinanqiao	3483	3483	0.00 %	3149	3149	0.00 %	2511	2511	0.00 %
	Longkaikou	2430	2432	0.08 %	2155	2158	0.14 %	1609	1613	0.25 %
	Cascaded	5913	5915	0.03 %	5304	5307	0.06 %	4120	4124	0.10 %
C2	Jinanqiao	3483	3483	0.00 %	3483	3483	0.00 %	3483	3483	0.00 %
	Longkaikou	2430	2432	0.08 %	2155	2158	0.14 %	1609	1613	0.25 %
	Ludila	2917	2920	0.10 %	2638	2641	0.11 %	1965	1970	0.25 %
	Cascaded	8830	8835	0.06 %	8276	8282	0.07 %	7057	7066	0.13 %
C3	Ahai	2645	2645	0.00 %	2423	2423	0.00 %	1810	1810	0.00 %
	Jinanqiao	3479	3485	0.17 %	3145	3149	0.13 %	2499	2506	0.28 %
	Longkaikou	2423	2427	0.17 %	2151	2156	0.23 %	1606	1613	0.44 %
	Ludila	2917	2921	0.14 %	2636	2640	0.15 %	1963	1971	0.41 %
	Cascaded	11464	11478	0.12 %	10355	10368	0.13 %	7878	7900	0.28 %
C4	Liyuan	2979	2979	0.00 %	2633	2633	0.00 %	2074	2074	0.00 %
	Ahai	2647	2650	0.11 %	2424	2428	0.17 %	1810	1813	0.17 %
	Jinanqiao	3480	3488	0.23 %	3150	3158	0.25 %	2506	2517	0.44 %
	Longkaikou	2429	2436	0.29 %	2161	2169	0.37 %	1616	1626	0.62 %
	Ludila	2924	2932	0.27 %	2648	2657	0.34 %	1976	1988	0.61 %
	Cascaded	14459	14485	0.18 %	13016	13045	0.22 %	9982	10018	0.36 %
C5	Liyuan	2981	2981	0.00 %	2636	2636	0.00 %	2076	2076	0.00 %
	Ahai	2648	2653	0.19 %	2426	2432	0.27 %	1814	1821	0.41 %
	Jinanqiao	3485	3497	0.35 %	3152	3167	0.48 %	2507	2525	0.74 %
	Longkaikou	2427	2439	0.48 %	2159	2172	0.62 %	1614	1631	1.05 %
	Ludila	2923	2935	0.40 %	2645	2660	0.55 %	1972	1993	1.04 %
	Guanyinyan	4016	4035	0.49 %	3638	3662	0.65 %	2618	2651	1.25 %
	Cascaded	18479	18539	0.32 %	16657	16730	0.44 %	12600	12697	0.76 %

Noting: C is Combination

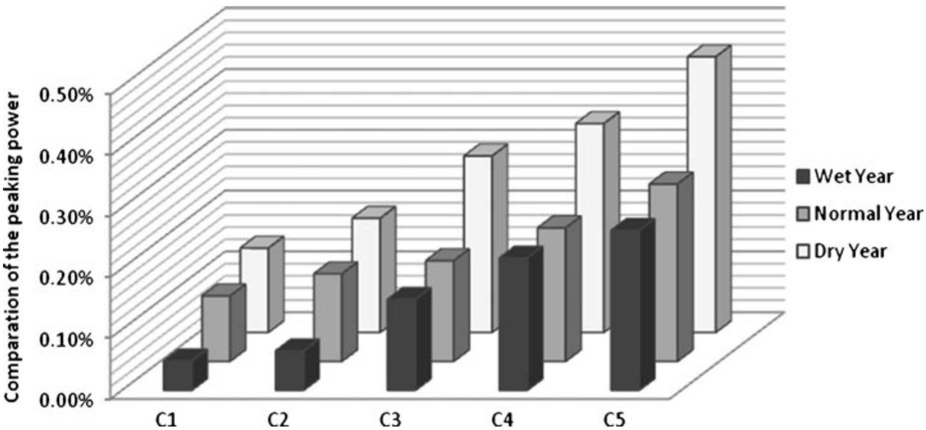

Fig. 9 The growth of total peaking power capacity for each combination and each typical year

normal year because of the relative sufficient water inflow. Then in result the advantages of the combined operation are not very obvious. But in dry year, the advantages of the combined operation in expanding the output regulation range are expressed better because of the less water inflow. It can be seen clearly from the following three dimensional graphs (Fig. 9).

Under the mode of daily load scheduling, another target of the same self-optimization simulation model is to ensure the maximum peaking capacity as far as possible, and the results of peak regulation are shown in Table 6.

The overall analysis of the table data shows that, for the five combinations in the different startup periods, the total peaking power capacity of the combined operation has increased in a certain degree comparing to the separated operation, and the average growth percentage of the daily peaking power capacity is between 0.05 % and 0.45 %. And this growth is proportional to increase along with the increasing number of the power stations in the combination. In view of the three typical years, the peaking power growth of each combination in dry year is higher than in wet year and normal year. The analyzed results are shown in the following three dimensional graphs (Fig. 9).

Table 6 Total peaking power capacity for each combination and each typical year

Name	Reservior	Wet year			Normal year			Dry year		
		Sep	Com	Growth	Sep	Com	Growth	Sep	Com	Growth
C1	Jinanqiao	1219	1219	0.00 %	1102	1102	0.00 %	879	879	0.00 %
	Longkaikou	851	852	0.12 %	754	756	0.27 %	563	565	0.36 %
	Cascaded	2070	2071	0.05 %	1856	1858	0.11 %	1442	1444	0.14 %
C2	Jinanqiao	1219	1219	0.00 %	1102	1102	0.00 %	879	879	0.00 %
	Longkaikou	851	852	0.12 %	754	756	0.27 %	563	565	0.36 %
	Ludila	1021	1022	0.10 %	923	925	0.22 %	688	690	0.29 %
	Cascaded	3091	3093	0.06 %	2779	2783	0.14 %	2130	2134	0.19 %
C3	Ahai	926	926	0.00 %	848	848	0.00 %	634	634	0.00 %
	Jinanqiao	1218	1220	0.16 %	1101	1103	0.18 %	875	878	0.34 %
	Longkaikou	848	850	0.24 %	753	755	0.27 %	562	564	0.36 %
	Ludila	1021	1023	0.20 %	923	925	0.22 %	687	690	0.44 %
	Cascaded	4013	4019	0.15 %	3625	3631	0.17 %	2758	2766	0.29 %
C4	Liyuan	1043	1043	0.00 %	922	922	0.00 %	726	726	0.00 %
	Ahai	926	928	0.22 %	848	850	0.24 %	634	635	0.16 %
	Jinanqiao	1218	1221	0.25 %	1103	1105	0.18 %	877	881	0.46 %
	Longkaikou	850	853	0.35 %	756	759	0.40 %	566	569	0.53 %
	Ludila	1023	1026	0.29 %	927	930	0.32 %	692	696	0.58 %
	Cascaded	5060	5071	0.22 %	4556	4566	0.22 %	3495	3507	0.34 %
C5	Liyuan	1043	1043	0.00 %	922	922	0.00 %	726	726	0.00 %
	Ahai	926	928	0.22 %	848	850	0.24 %	634	635	0.16 %
	Jinanqiao	1218	1221	0.25 %	1103	1105	0.18 %	877	881	0.46 %
	Longkaikou	850	853	0.35 %	756	759	0.40 %	566	569	0.53 %
	Ludila	1023	1026	0.29 %	927	930	0.32 %	692	696	0.58 %
	Guanyinyan	1407	1413	0.43 %	1275	1282	0.55 %	919	927	0.87 %
	Cascaded	6467	6484	0.26 %	5831	5848	0.29 %	4414	4434	0.45 %

The middle reaches of hydropower station operation plan and formulates the scheduling rules Power operation plan and scheduling rules of cascade hydropower stations in Jinsha River middle reaches research.

6 Conclusion

This study applied the characteristics of self-optimization simulation technology, such as the clear physical meaning, more perfect simulation, no dimension limitation, artificial adjustment with the accumulated experience and so on. Simultaneously giving enough thought to the requirements of the daily load curve, a self-optimization simulation model was developed for the short-term cascaded hydroelectric system scheduling. This model took both of the supply and demand sides' requirements into account. The first task was to keep power grids operate safely and stably, and then pursued the maximum total power generation capacity and the maximum peaking capacity. The methodology was implemented for the cascaded hydroelectric system in the middle reaches of Chinese Jinsha River under the conditions of different production periods and combinations. From the table and figure data above, as to the station of each combination with different startup time, whether for the total generating capacity or the peaking power, it had been demonstrated that there was probable improvement of comprehensive benefits comparing the combined operation to the separated operation. Because the combined operation could embody the advantages of the electricity and hydraulic contacts well. The average growth rate of combination operation is between 0.20 % and 48 %, and the additional generation capacity of each year is between 132 million kilowatt-hours and 279 million kilowatt-hours. Viewing on the contribution to the social benefit, the above data was about relative 5.8~13.0 ten thousand tons coal saved, or 13.4~29.7 ten thousand tons carbon dioxide emissions reduced. So the demonstrated results were of great help for the different development bodies to implement the combined operation, and had important significance in implementing the national policy of energy-saving and emission reduction.

Although this study is the first attempt for solving the multi-objective short cascaded hydropower scheduling problem with the self-optimization simulation technology, the special solving method makes the operation plans satisfactory, and it is more probable to put this scheduling scheme into practice. When the leading power plant has been demonstrated successfully and begins to operate in practice, it will generate a new significant subject of the combined operation with the eight cascaded hydropower station group. So the further study will be aimed at formulating the scheduling scheme of the eight cascaded hydropower station, and the plan inevitably plays an important part in transporting and utilizing the hydroelectricity in the middle reaches of Jinsha River.

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